Advanced Modelling and Control of attitude dynamics for CubeSat
01/10/2017 – 30/09/2020

Research environment:

- Laboratory: GIPSA-Lab, University Grenoble-Alpes, Grenoble, France (http://www.gipsa-lab.fr/)
- Topic of research: SCAO, data fusion, estimation and control in nano-satellites
- Collaboration with Hyperion Technologies, Netherlands HYPERION TECHNOLOGIES

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For application (before 5 June), please contact Hassen Fourati or Bogdan Robu !

Skills and knowledge: Automatic Control and Systems, Filtering and Estimation, Optimization, Data Fusion

Funding: Possible ministerial scholarship – application will be in June !

Context of PhD and state-of-the-art

Currently France is lagging behind, considering that only one nanosatellite has been launched, versus more than 200 for entire Europe. The CSUG (the Grenoble University Space Center, https://www.csug.fr/) has set for itself the ambitious goal of developing CubeSats that distinguish themselves from other university-developed nanosatellites by a maximum scientific return. The second satellite consortium is recently established by the CSUG and started its preliminary Phase-0 study in September 2016. The "NanoBob quantum CubeSat" or NanoBob CubeSat mission wants to design a new CubeSat and use it to demonstrate the experimental feasibility of a free space full quantum communication link over a distance greater than 500km to exchange a cryptographic key. The NanoBob CubeSat mission should demonstrate the feasibility to establish free-space quantum communication links between a ground station and an economically attractive nanosatellite (used as a node in the communication) adhering to the CubeSat standard. The transmitters to the satellite are located in Vienna and the Canary Island (see Fig. 1). GIPSA-Lab is one of the partners of this consortium, whose mission is to study and develop the Attitude (called also orientation) Determination and Control System (ADCS) of NanoBob.

Figure 1: mission configuration. Single (entangled) photons are sent from the Vienna telescope to the receiver on board of the NanoBob cubesat. Satellite control and data transmission is done by conventional radio communication.

The ADCS is used on-board to keep NanoBob almost perfectly aligned with the transmitter source located in Vienna. In fact, the NanoBob satellite will need to be oriented towards the photon source during a sufficiently long section of its overpass of the ground station telescope. In order to have a successful transmission and receiving of the photons, the satellite and the ground station should be aligned with less than ~100 arcsec (~0.03°) error (dynamic pointing stability of the ADCS). However, a full quantum up-link experiment may require a tracking with ~1 arcsec (0.00027°) error from the ground station, a level of precision that is not reached until now by the commercial ADCS's. A deep study of some projects shows that it is often needed that the satellite high-gain antenna used for communications points to the Earth with high accuracy so that on-board experiments may accomplish accurate collection and subsequent interpretation of data. Controlling the satellite attitude requires sensors to measure its orientation, actuators to apply the torques needed to re-orient the satellite to a desired attitude and algorithms to control the actuators based on: (1) sensor measurements of the current attitude and (2) specification of a desired attitude.

Pointing, acquisition and tracking of a targeted optical ground station with the specified small FOV of the detector is probably the most critical part of the experiment. The question of how to advance the current attitude estimation/control solutions for the nanosatellite NanoBob to reach the desired dynamic pointing stability within the proposed ADCS, is the main objective in the PhD program.

State-of-the-art on ADCS and objectives of PhD work

After knowing more concretely about how NanoBob will be, the PhD student will be able to compute its dynamic equations, depending on the considered concept. Later, two main different parts compose the ADCS: attitude determination followed by attitude control.

1. To control the attitude, the ADCS must have firstly the ability to determine the current attitude using specific on-board sensors. Many relative sensors generate outputs that reflect the rate of change in attitude such as gyroscopes. They require a known initial attitude, or external information, to use it in order to determine the current attitude. Many types of this class of sensors have noises leading to inaccuracies if not corrected by absolute attitude sensors such as: horizon sensor, sun sensor, star tracker, magnetometer, etc. The absolute attitude sensors feel the position or orientation of fields, objects or other phenomena outside the satellite. One of the first works related to this problem used least squares approach (Wahba, 1965). Later, various approaches are developed/tested, each one with some advantages and drawbacks (related to precision, complexity, robustness to noises, etc.), by using separately or combining relative and absolute sensors such as QUEST (QUaternion ESTimator) (Markley and Mortari, 2000), Extended QUaternion ESTimator (Psiaki, 2000), Kalman filters (Shuster, 1990 ; Lefferts et al., 1982), complementary filters (Mahony et al., 2008 ; Wu et al., 2016), observers (Koprubasi and Thein, 2006 ; McDuffie et Shtessel, 1997, Fourati et al., 2016), etc.
   The main conclusion is that attitude estimation for nanosatellites is still an open problem and an improvements on precision, complexity or robustness in presence of noises is still desirable. During the PhD we will mainly focus on sensor bias, noise, magnetic perturbations, which affect the estimation quality.
2. To re-orient the satellite to a desired attitude, some actuators are needed to apply the right torques such as reaction wheels, magnetic torquers, etc. From the other side, control algorithms are computer programs that receive data from vehicle sensors/estimation algorithms and compute the appropriate commands to the actuators in order to rotate the satellite to the desired attitude. As a non-exhaustive list we can note from the literature: PD controller (Fjellstad and Fossen, 1994), H2 controller (Parlos and Sunkel, 1992), Hinf controller (Ballois and Duc, 1996) or (Robu and al, 2012), H2/Hinf controller (Limebeer and al., 1994), sliding mode controller (Wang and al., 1998), state and output feedback control (Lovera and Astolfi, 2004).
   The main conclusion is that there is no comparison between all of them and a clear conclusion about their performance. Some of these methods are not applied in real case scenarios therefore it is difficult to verify the announced precision of pointing. We remarked also that dynamic pointing stability we want to reach, i.e., a tracking with ~1 arcsec (0.00027°), is very hard to keep. We need to analyse recurrent problems in the ADCS (the effect of disturbances, recurrent noises and their frequencies, stability, external perturbations, modelling errors, etc.) in order to satisfy the dynamic pointing precision required for NanoBob.

Complementary information

- This PhD thesis will benefit from the ongoing study on these aspects done by Jean-Yves Burlet an engineer student (2nd year) from “Ecole Centrale de Lyon” during his internship in GIPSA-Lab (January-May 2017). He revisited/analysed the scientific development of ADCS to identify the strengths/drawbacks and take advantage of previous experiences and projects.
- The PhD program, is in strong collaboration with Mathieu Barthélémy (astrophysicist and director of the CSUG), Erik Kerstel (Professor in physics, he is the scientific PI of the NanoBob mission and will help define the mission specifications), and Thierry Sequies (Research Technician at UGA).
- Discussions and collaborations with Hyperion Technologies[1] Netherlands, which is interested to improve and space test their latest ADCS on a CubeSat. This collaborations will be the opportunity for the PhD student to test the developed approaches with experimental data.

Bibliography

G. Wahba, A Least Squares Estimate of Satellite Attitude, *SIAM Rev.*, vol. 7, no. 3, 409–409, 1965.

L. F. Markley, and D. Mortari, Quaternion Attitude Estimation Using Vector Observations, *The Journal of the Astronautical Sciences*, vol. 48, 2000.

M. L. Psiaki, Attitude-Determination Filtering via Extended Quaternion Estimation, *Journal of Guidance, Control and Dynamics*, vol. 23, no. 2, 2000.

M. D. Shuster, Kalman filtering of spacecraft attitude and the QUEST model, *Journal of the Astronautical Sciences*, vol. 38, no. 3, 377–393, 1990.

R. Mahony, T. Hamel, and J-M. Pflimlin, Nonlinear Complementary Filters on the Special Orthogonal Group, *IEEE Trans. On Automatic Control,* vol. 53, no. 5, 2008.

[1] http://hyperiontechnologies.nl/

K. Koprubasi, and M-W L. Thein, Attitude and Angular Rate Estimation Using the Sliding Mode Observer with Multiplicative Quaternion Corrections for the Cooperative Astrophysics Technology SATellite (CATSAT), *IEEE American Control Conference*, Minnesota, USA, 2006.

J. H. McDuffie, Y. B. Shtessel, A de-coupled sliding mode controller and observer for satellite attitude control, *IEEE*, 1997.

E. J. Lefferts, F. L. Markley, and M. D. Shuster, Kalman Filtering for Spacecraft Attitude Estimation, *AIAA Journal of Guidance*, vol. 5, no. 5, 417-429, 1982.

V. Unhelkar, Satellite Attitude Estimation using Sun Sensors, Horizon Sensors and Gyros, *Master of Technology*, Indian Institute of Technology, Bombay, 2012.

A. G. Parlos, and J. W. Sunkel, Adaptive Attitude Control and Momentum Management for Large-Angle Spacecraft Maneuvers, *Journal of Guidance, Control, and Dynamics*, vol. 15, no. 4, 1018-1028, 1992.

S. L. Ballois and G. Duc, H∞ Control of an Earth Observation Satellite, *Journal of Guidance, Control, and Dynamics*, vol. 19, no. 3, 628-635, 1996.

D. J. N. Limebeer, B. D. O. Anderson, and B. Hendel, A Nash Game Approach to Mixed H2/H-infinity Control, *IEEE Transactions on Automatic Control*, vol. 39, no. 1, 69-82, 1994.

P. Wang, Y. B. Shtessel, and Y. Q. Wang, Satellite attitude control using only magnetorquers, 13th Southeastern Symposium on System Theory, West Virginia University, Morgantown, WVa, USA, 1998.

M. Lovera and A. Astolfi, Spacecraft attitude control using magnetic actuators, *Automatica*, vol. 40, no. 8, 1405-1414, 2004.

O. E. Fjellstad, and T. I. Fossen, Comments on the attitude control problem, *IEEE Transactions on Automatic Control,* vol. 39, no. 3, 699-700, 1994.

J. Wu, Z. Zhou, J. Chen, H. Fourati, and R. Li. Fast Complementary Filter for Attitude Estimation Using Low-Cost MARG Sensors. *IEEE Sensors Journal*, vol. 16, no.18, pp. 6997-7007, September 2016.

H. Fourati, and D. E. C. Belkhiat, Recent Advances on Multisensor Attitude and Heading Estimation: Fundamental Concepts and Applications. *Series: Devices, Circuits, and Systems, CRC Press*, Taylor & Francis Group LLC, ISBN: 9781498745710, 580 pages, Aug. 2016.

B. Robu, L. Baudouin, C. Prieur, and D. Arzelier. Simultaneous Vibration Control of Fluid/Plate System via Reduced-Order Controller. *IEEE Transactions on Control Systems Technology*, vol. 20, no. 3, pp. 700-711, 2012.